Joint Institute for High Temperatures
Russian Academy of Sciences, Moscow

Shock, ablation and formation of nanostructures in metals induced by femtosecond laser

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MOTIVATION

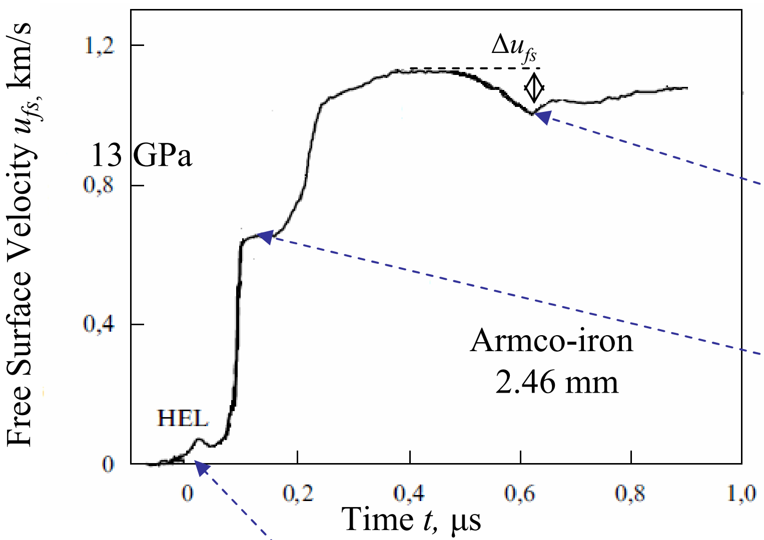
- ✓ Laser matter interaction/ experiment and modeling
- ✓ Materials behavior near the theoretical limit of shear and bulk strength
- ✓ Development of a theory of plasticity and fracture
- ✓ Femtosecond laser surface nanostructuring

OUTLINE

- ✓ Shock compression of aluminum and iron in picosecond range.
  - super elastic shock waves at submicron scale
  - achievement of ultimate values of the shear and bulk strength
  - possibility of $\alpha \rightarrow \varepsilon$ polymorphic phase transition in iron
- ✓ Frontal ablation and rear side spallation of aluminum.
- ✓ Formation of nanostructures: MD simulations and experiment

Shock compression of metals. Appearance of material properties in a free surface history. Shock wave structure.

Free surface velocity history
In plate impact experiment*.



Diagnostics of shock phenomena are performed by measuring a free surface velocity profile of a tested sample.

Reflection of shock compression pulse from the free surface leads to appearance of the tensile stresses inside of the sample causing fracture. Value of spall strength is determined from:

$$\sigma_{spall} = \rho_0 U_S (\Delta u_{fs} + \delta) / 2$$

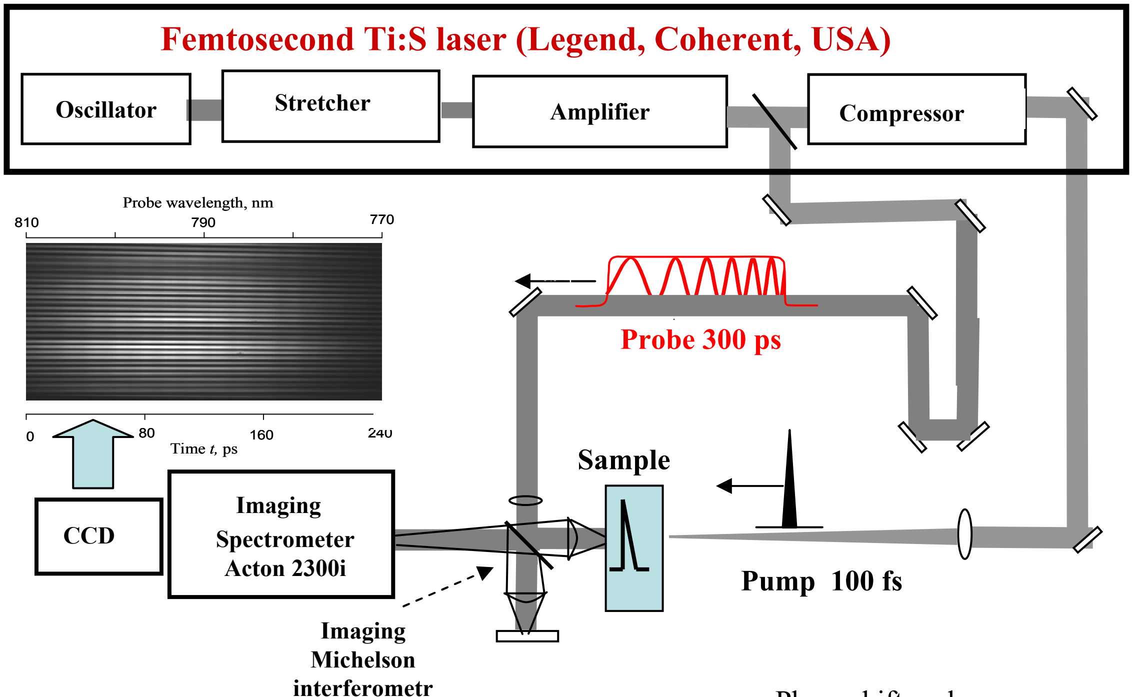
α⟶ε polymorphic phase transition in iron:
(bcc ⟶ hcp crystal structure transition)
Transition stress ≈13GPa in a microsecond range

Splitting of shock wave into elastic precursor (HEL) and plastic compression wave makes it possible to determine the plasticflow stress of the material.

$$\sigma_{HEL} = \rho_0 U_S^e \Delta u_{fs}^e / 2$$

* G.I. Kanel', V. E. Fortov,S.V. Razorenov *Physics-Uspekhi* **50,** (8) (2007)

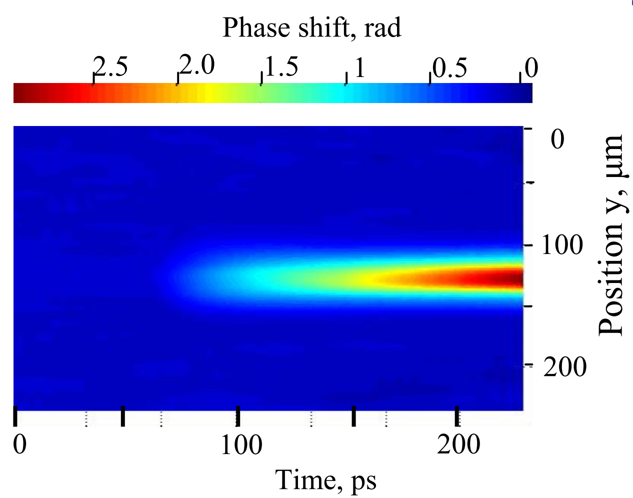
Ultrafast Chirped Pulse Interferometry



- Detected range 0 ÷ 240 ps
- Temporal resolution 1ps
- Lateral spatial resolution 2 μm
- Displacement accuracy 1÷2 nm
- Measurements in a single shot

In contrast to multipulse pump–probe methods the single-pulse technique ensures much higherreliability of the measurements and can be used to analyze the reproducibility and statistics of shock wave phenomena in thin film samples.

2D Fourier processing of interference patterns

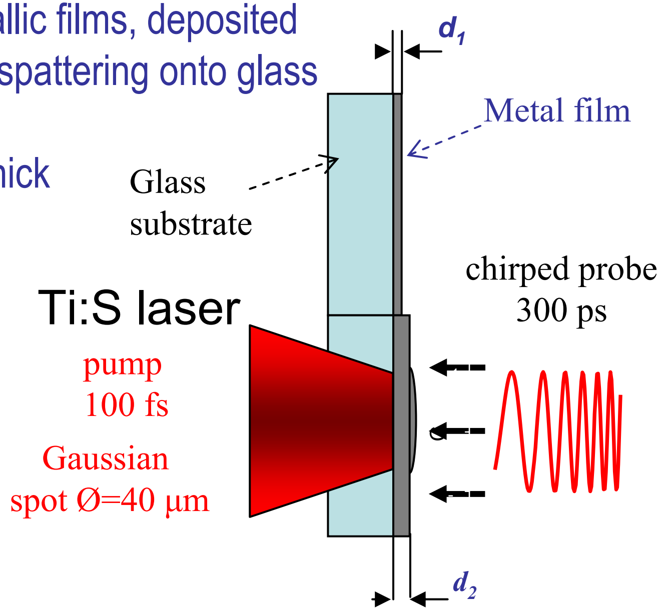


Spatial-temporal phase distribution

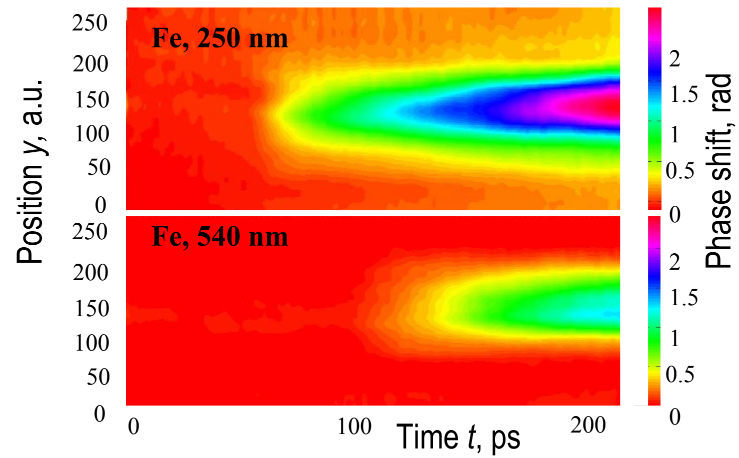
Application of Fourier processing of interference patterns and comparison of phase distributions obtained before and during shock wave arrival ensure measurement of surface displacement with nanometric accuracy.

Time and spatial resolved diagnostics of a rear surface displacement

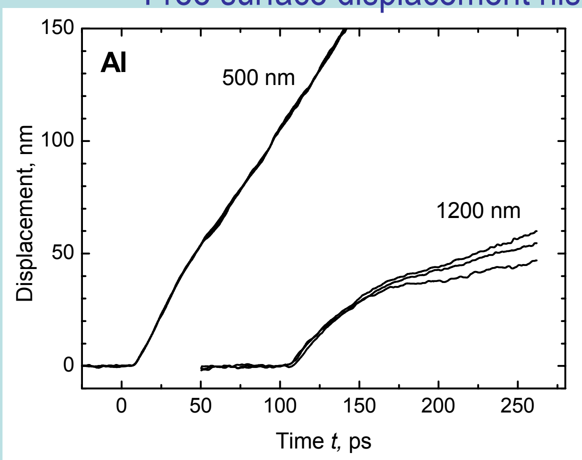
Samples: metallic films, deposited by magnetron spattering onto glass substrates
of 150 μm in thick

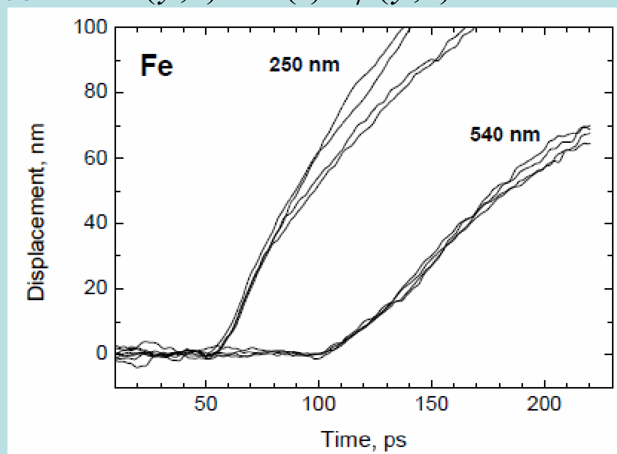


Phase distributions $\Delta\varphi(y,t)$ at the rear surface of iron targets of different thicknesses after shock breakout



Free surface displacement histories $\Delta z(y,t) = \lambda(t)\Delta\varphi(y,t)/4\pi$



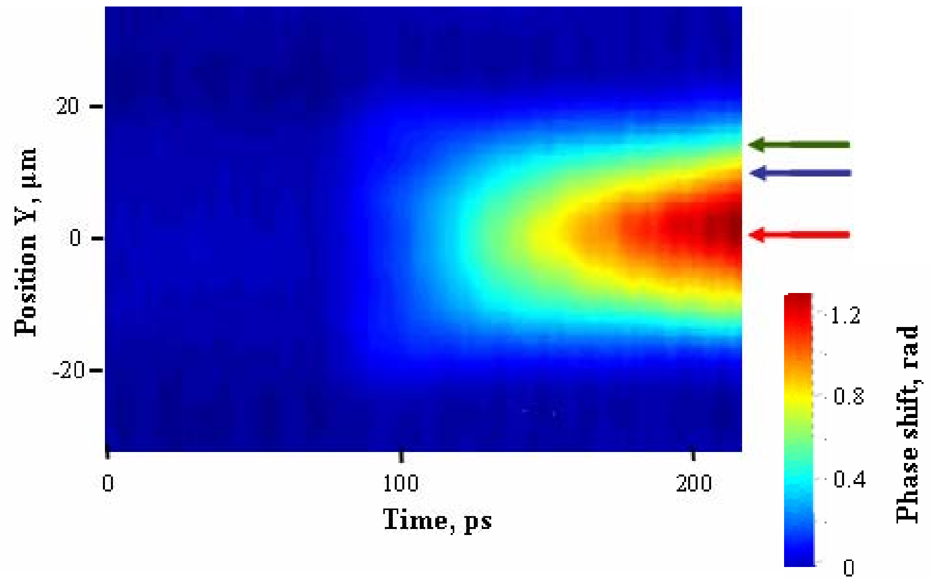


Elastic-plastic shock wave in iron

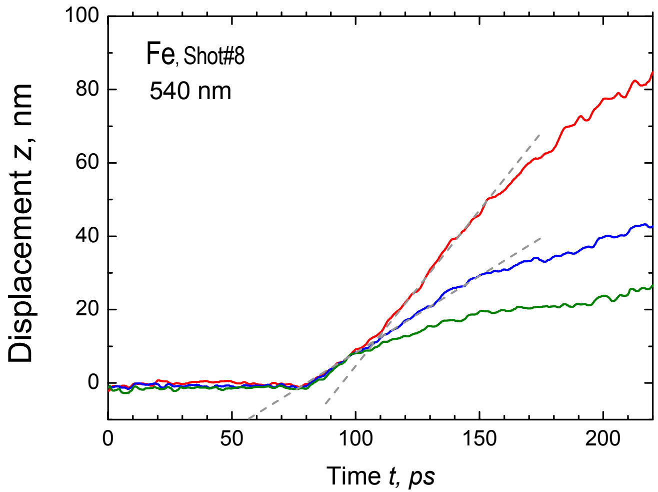
Ti:S laser: 100fs, 3 J/cm

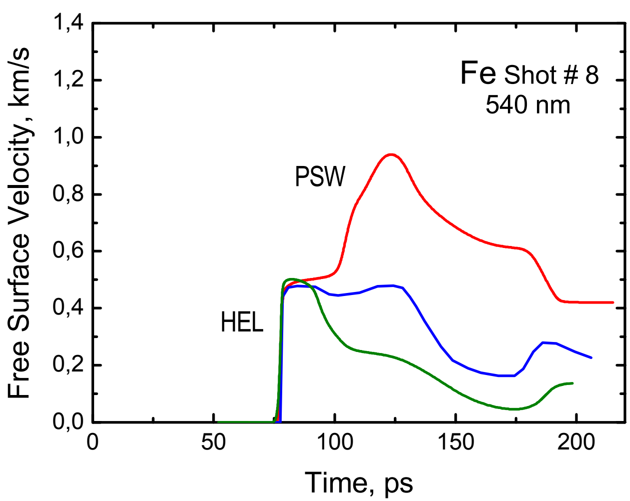
Sample: 99.9 purity iron film 540 nm in thick deposited on glass substrate

Splitting of shock into elastic-plastic two-wave configuration at propagation distance of 540 nm



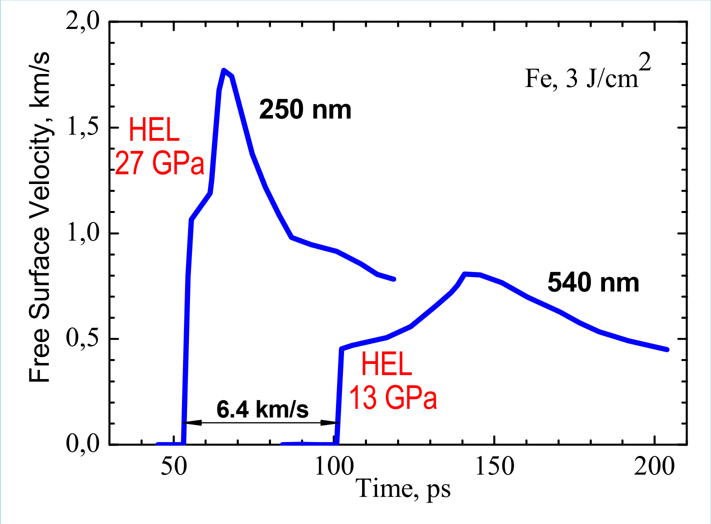
Free surface displacement and velocity history at different stress

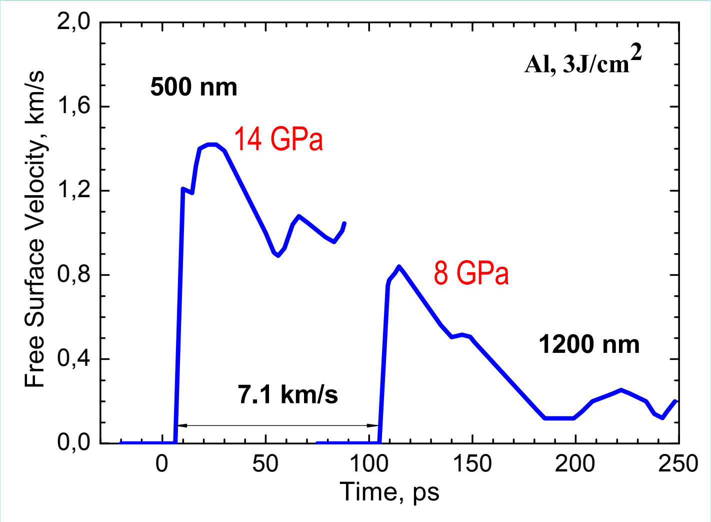




Evolution of laser driven shock waves in Al and Fe at a submicron scale. Elastic Hugoniout

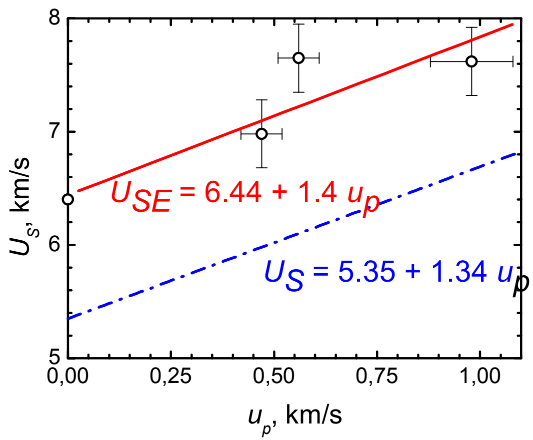
Free surface velocity histories

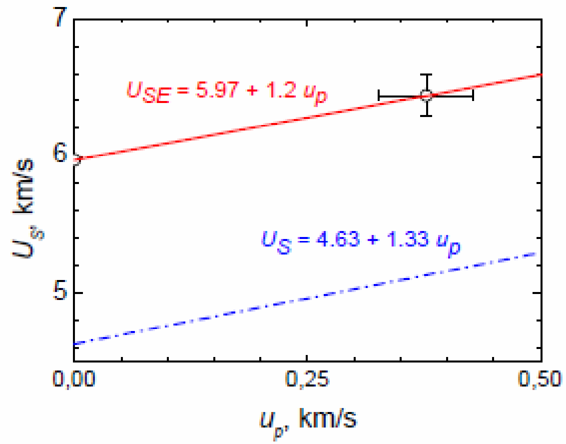




$U_S - u_p$ diagrams. Elastic Hugoniout.

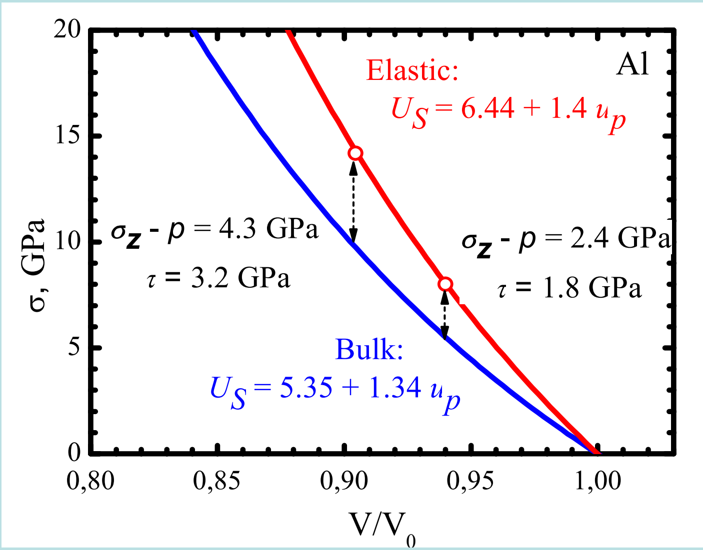
- In iron splitting of shock wave into two-zone elastic-plastic configuration was observed
- In aluminum pure elastic wave was detected at stress up to 14 GPa with parameters rise time of 1-2 ps

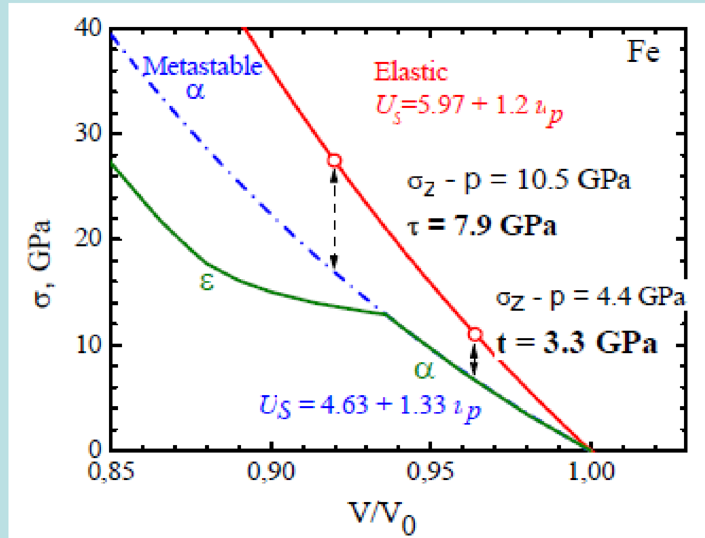




$P - V$ diagrams. Shear strength of aluminum and iron

Recorded states in elastic shock waves (points) in aluminum and iron films



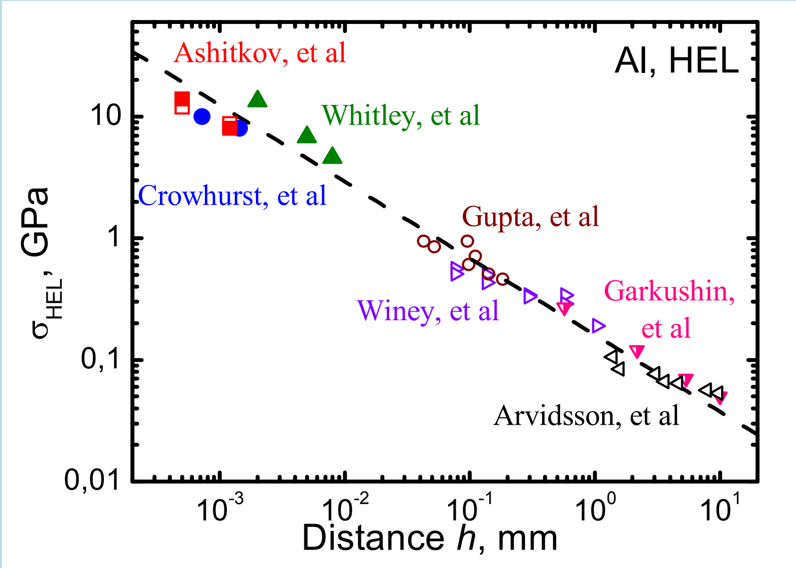


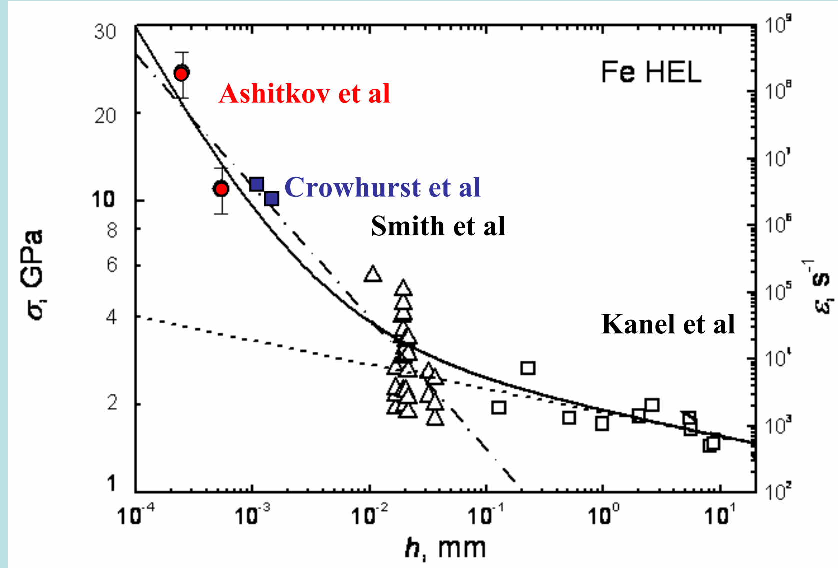
Maximum shear stress at uniaxial compression:

$$\tau = \frac{3}{4}(\sigma_z(V) - p(V))$$

	Experimental value	Theoretical limit
Al	**up to 3.2 GPa**	**3.4 GPa**
Fe	**up to 7.9 GPa**	**7.5 GPa**

Decay of the elastic precursor in aluminum and iron





$$\sigma_{HEL} = S\ (h/h_0)^{-0.63}$$

$$\sigma_{HEL} = S_1(h/h_0)^{-0.45} + S_2(h/h_0)^{-0.083}$$

- Super elastic shock waves with the stress >10 GPa were detected at submicron propagation distance
- Decay of the elastic precursor is connected with plastic strain rate $\dot{\gamma}_p$:

$$\left.\frac{d\sigma_x}{dh}\right|_{HEL} = -\frac{4}{3}\frac{G\dot{\gamma}_p}{c_l}$$

(G - shear modulus)

□ S.I.Ashitkov, et al *JETP. Lett.* **92**, 516 (2010)
▲ V. H. Whitley, et al *J.Appl. Phys.* **109**, 013505 (2011)
● J.C.Crowhurst, et al *Phys.Rew.Lett.* **107**, 144302 (2011)

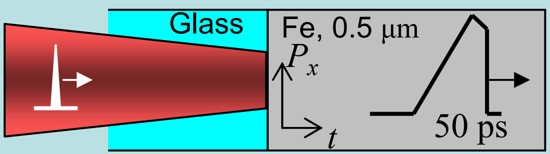
● S.I. Ashitkov, et al *JETP Lett.* **98**, 384(2013)
■ J.C.Crowhurst, et al *J.Appl. Phys.* **115**, 113506 (2014)

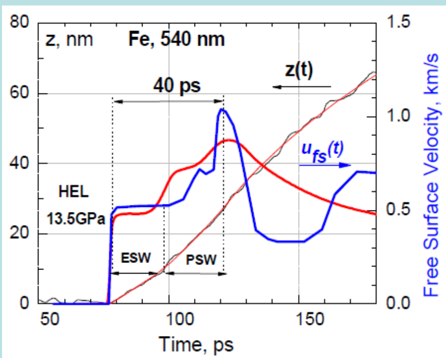
The α → ε phase transition in iron at strain rate ~10^9 s^{-1}

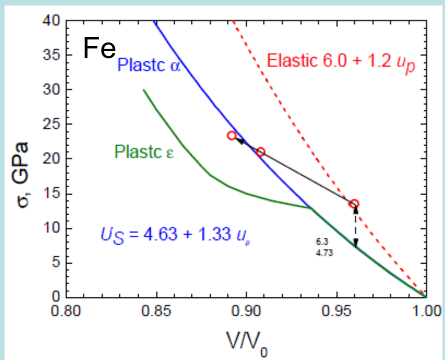
JIHT of RAS, 2013

Laser, 100 fs

Sample: Fe film on a glass substrate





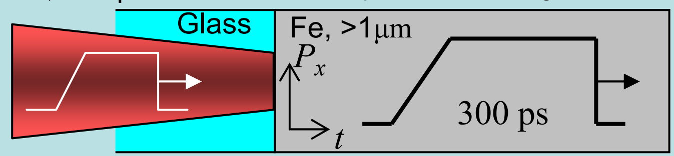


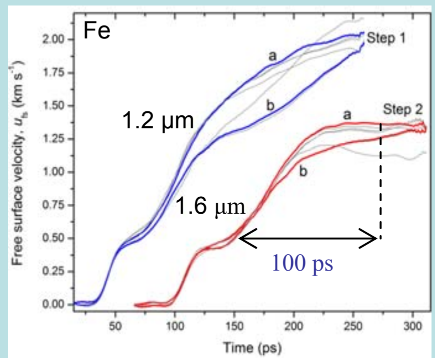
- HEL = 13-14 GPa at propagation distance 0.54 μm
- deviatoric stress 4.5 GPa
- PSW stress is up to 23GPa
- observation of a trend to splitting PSW into two waves
- but α→ε polymorphic transition in iron isn't realized within 20 ps

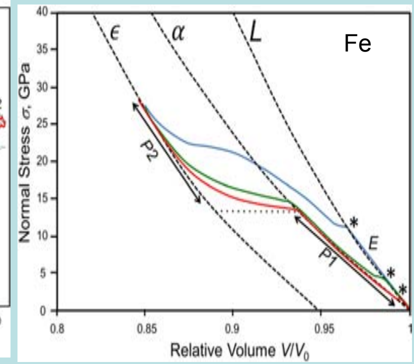
LLNL Livermore, 2013

Laser, 300 ps

Sample: Fe film on a glass substrate



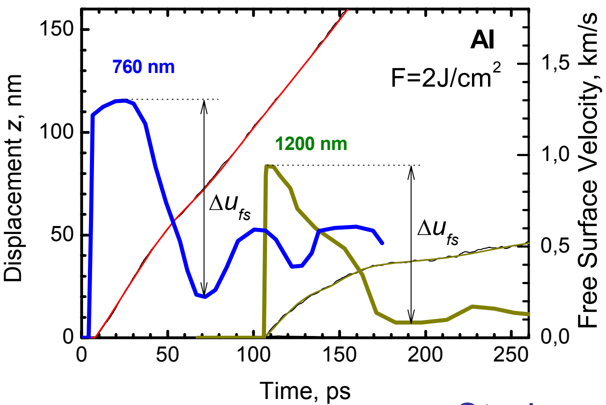




- HEL = 10-12 GPa at propagation distance 1.2-1.6 μm
- deviatoric stress exceeds 3 GPa
- transition stress is up to 25GPa
- α→ε polymorphic transition in iron is realized within 100 ps

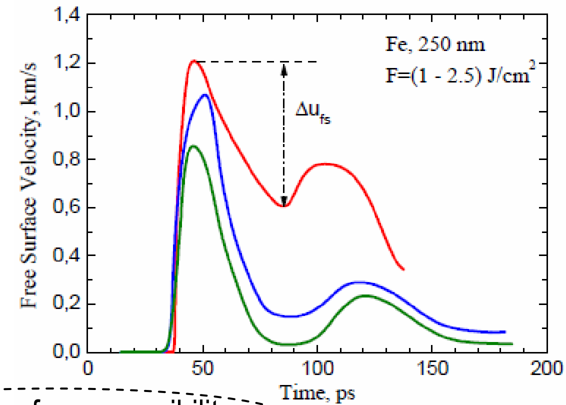
J.C. Crowhurst et al, J.Appl. Phys. **115**, 113506 (2014)

Spall strength of aluminum and iron at strain rate ~ 10^8 - 10^9 s^{-1}



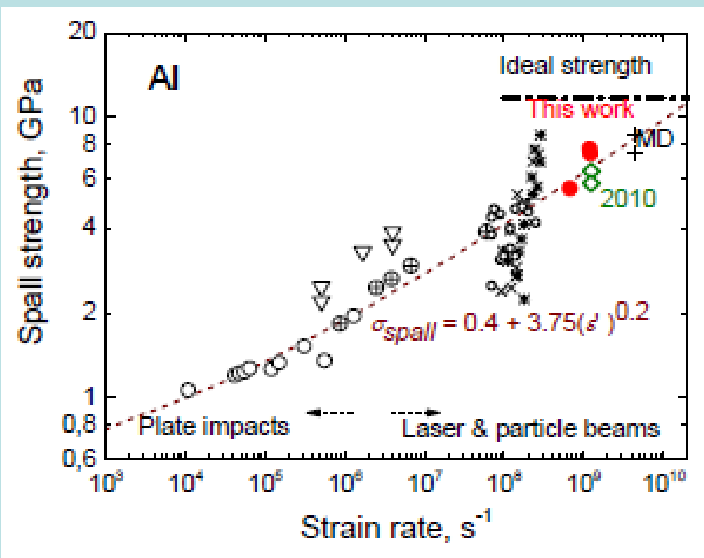
Free surface velocity histories indicate spallation at a pure elastic uniaxial compression in a picosecond range

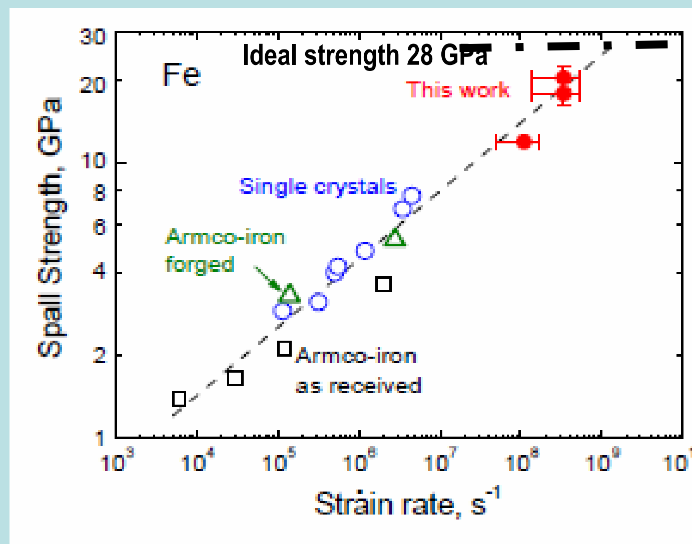
$$\sigma_{spall} = \frac{1}{2}\rho_0(c_l - b\,\Delta u_{fs}/2)\Delta u_{fs}$$



Strain rate $\dot{V}/V_0 = \dot{u}_{fs}/2c$

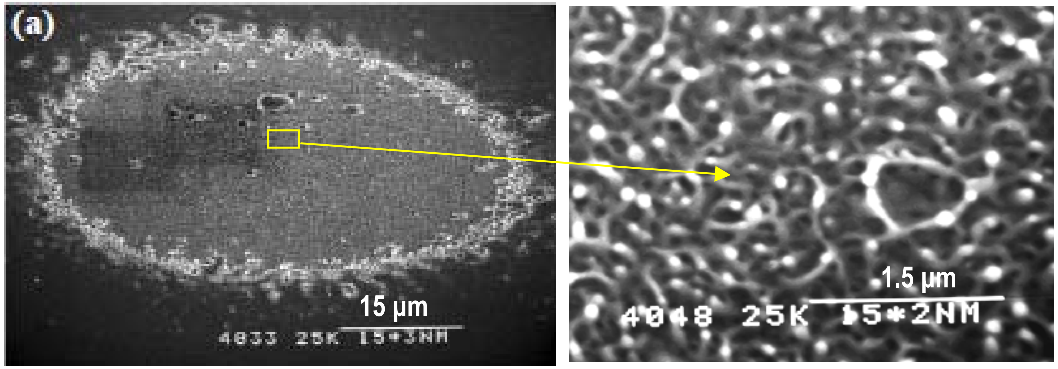
nonlinearity of compressibility



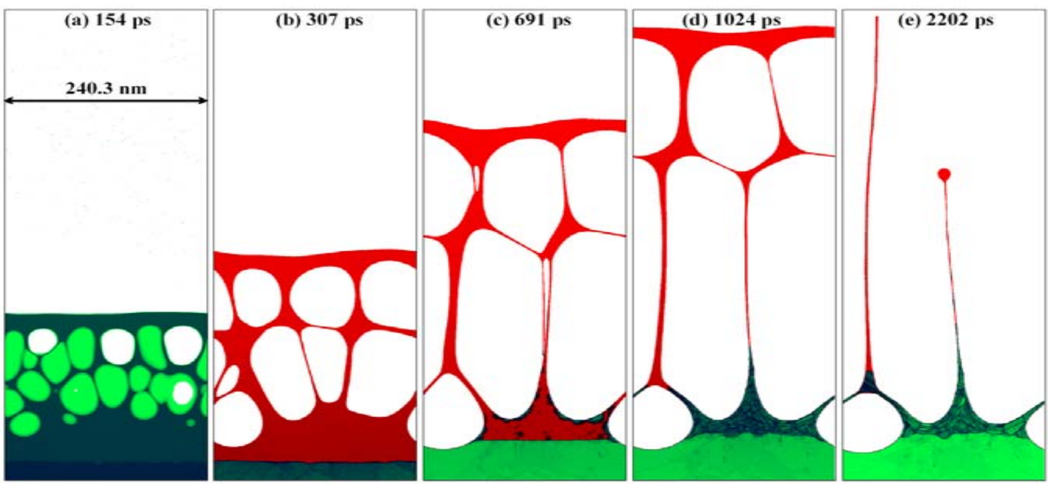


S.I.Ashitkov, et al *JETP. Lett.* 92, 516 (2010)

Formation of nanostructures on metal surface after femtosecond laser irradiance above ablation threshold



SEM images of ablation crater at a surface of gold sample.
Laser: 100 fs; F/Fabl=1.5



(a) - density map (b-e) - atomic order map: solid (green), liquid (red)

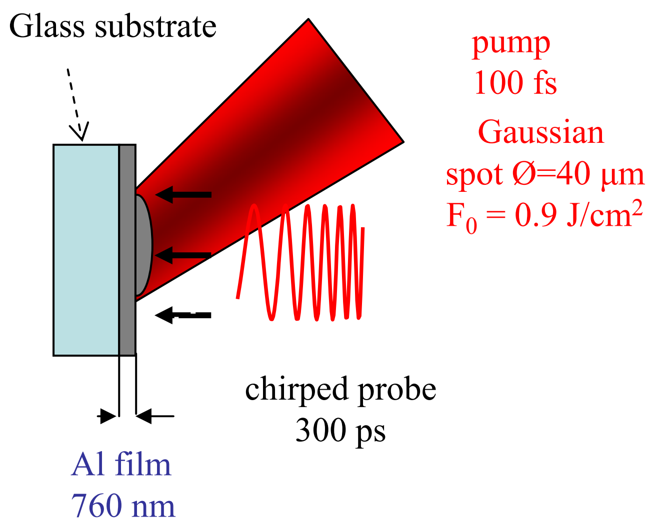
Result of long large-scale MD simulation of a sample with dimensions
$L_xL_yL_z$ = 500x240x24 nm^3
and 172×10^6 atoms.
Laser: 100 fs; F/F abl =1.5

Expansion of foam,breaking of membranes, and freezing the remnants of membranes near the transit between foam and continuous metal.

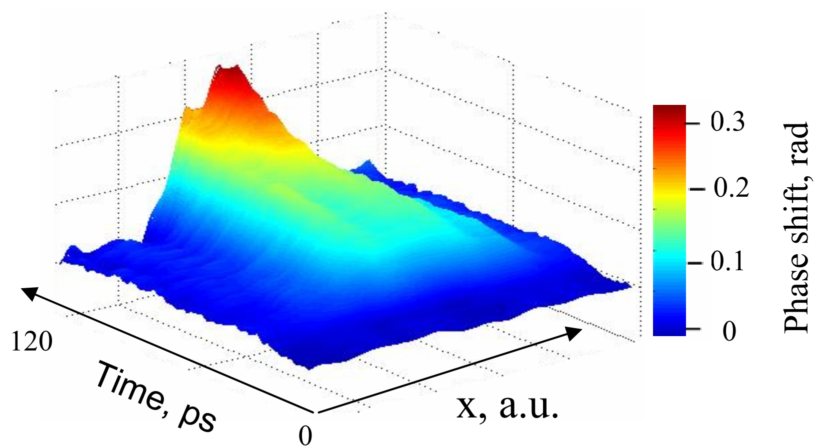
N.A. Inogamov, et al *Contr.Plasma Phys*. 53, 796 (2013)

Dynamics of surface layer expansion during femtosecond ablation of aluminum

Ti:S laser

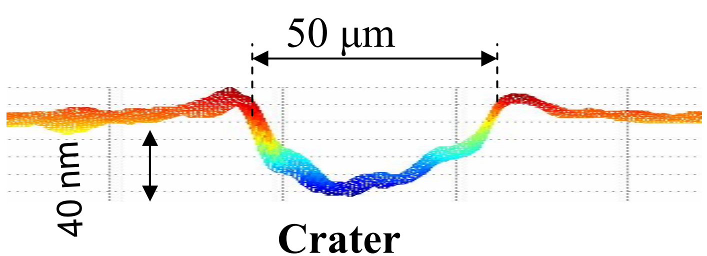


Temporal spatial phase distribution

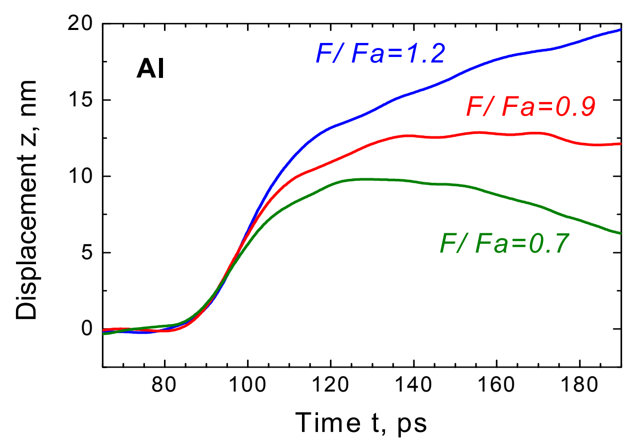


Ablation threshold 0.7 J/cm^2

Profile of ablation crater

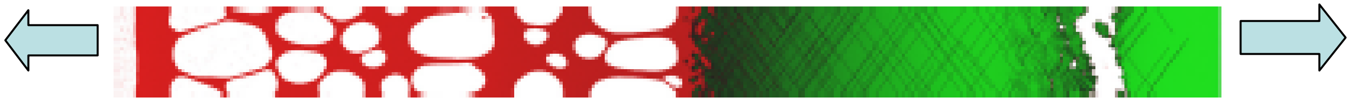


Displacement history



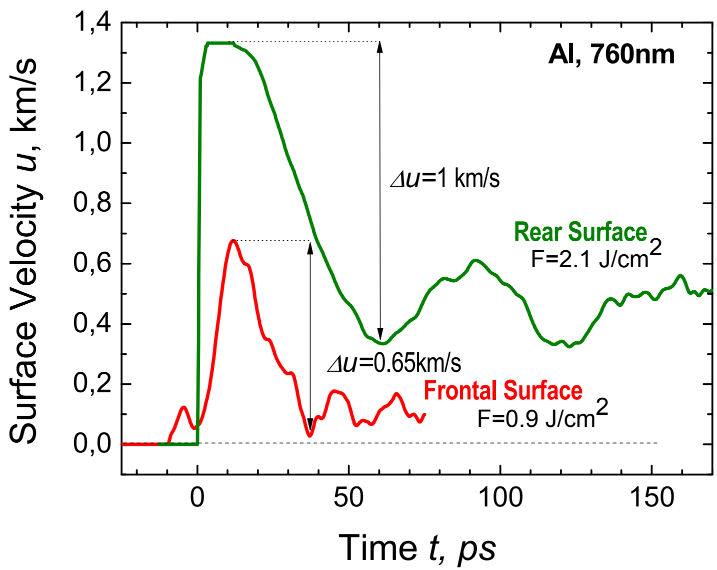
Frontal and rear side spallation in aluminum

Frontal surface | Map of local atomic order | Rear surface



Ti:S laser, 100 fs

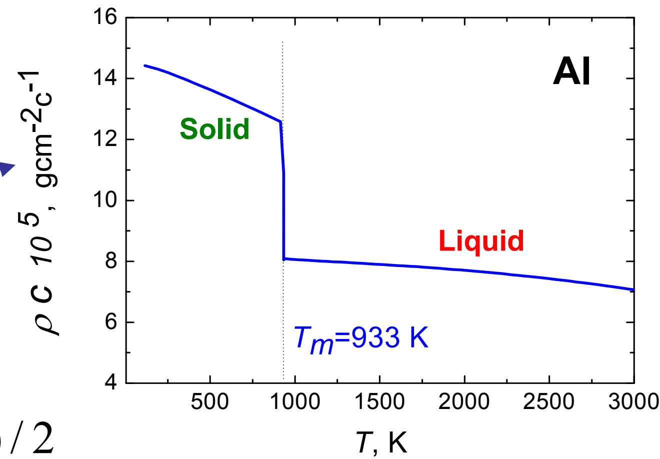
Frontal and rear surface velocity history



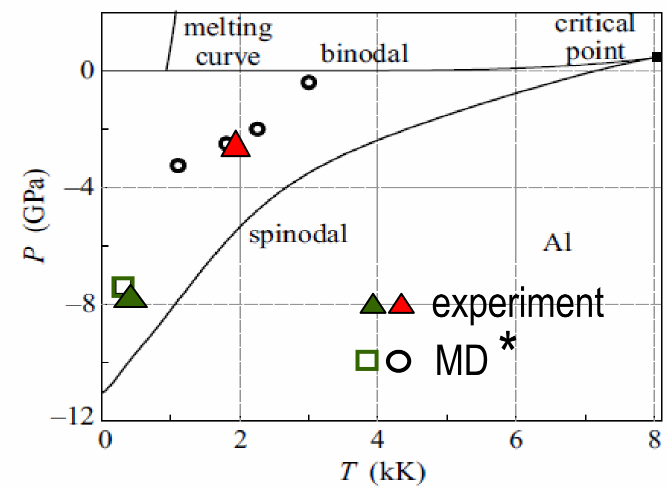
$$\sigma_{spall} = \rho c \Delta u / 2$$

$$\dot{\varepsilon} = \dot{u}_{fs} / 2c$$

$$L_{spall} = c(t_{\min} - t_{\max}) / 2$$



Al	ρ, gcc	c, km/s	$\dot{\varepsilon}$, s^{-1}	σ_{Spall}, GPa	L_{Spall}, nm
Solid (300 K)	**2.71**	**6.4**	**$2\cdot10^9$**	**7.7±0.5**	**250**
Liquid (2kK)	**2.16**	**3.6**	**$3\cdot10^9$**	**2.5±0.5**	**45**



* N.A.Inogamov et al JETP Lett 91 (2010)

JIHT of RAS

SUMMARY

✓ Single shot interferometric diagnostics was realized to measure surface displacement history with temporal resolution of 1 ps.

✓ Experimentally found that uniaxial shock compression in picosecond range is elastic up to stress of 14 GPa in aluminum and 27 GPa in iron.

✓The stressed states in aluminum and iron, very close to the values of ultimate shear and bulk strength were measured and implemented in picosecond range of load duration

✓The $\alpha \rightarrow \varepsilon$ polymorphic phase transition in iron film of 540 nm in thick isn't realized at a stress of 23 GPa within 20 ps after HEL

✓ From the expansion surface history the value of tensile stress of about 2.5 GPa leads to spallation of liquid layer of aluminum just above the ablation threshold under femtosecond heating was measured.

✓ The results of long large-scale MD simulations of nanostructures formation at metal surface after it's irradiance of femtosecond laser is well similar to SEM images of ablation crater's morphology

Thank you for your attention!